Integrated Test and Evaluation of a 4-Bed Molecular Sieve (4BMS) Carbon Dioxide Removal System (CDRA), Mechanical Compressor Engineering Development Unit (EDU), and Sabatier Engineering Development Unit (EDU)

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Abstract

Currently on the International Space Station's (ISS) U.S. Segment, carbon dioxide (CO_2) scrubbed from the cabin by a 4-Bed Molecular Sieve (4BMS) Carbon Dioxide Removal Assembly (CDRA) is vented overboard as a waste product. Likewise, the product hydrogen (H_2) that will be generated by the Oxygen Generation Assembly (OGA) planned for installation will also be vented. A flight experiment has been proposed that will take the waste CO_2 removed from the cabin, and via the catalytic Sabatier process, reduce it with waste H_2 to generate water and methane. The water produced may provide cost and logistics savings for ISS by reducing the amount of water periodically re-supplied to orbit. To make this concept viable, a mechanical piston compressor and accumulator were developed for collecting and storing the CO_2 from the CDRA. The compressor, accumulator and Sabatier system would be packaged together as one unit and referred to as the Carbon Dioxide Reduction Assembly (CRA). Testing was required to evaluate the performance of a 4BMS CDRA, compressor, accumulator, and Sabatier performance along with their operating rules when integrated together. This had been numerically modeled and simulated; however, testing was necessary to verify the results from the engineering analyses. Testing also allowed a better understanding of the practical inefficiencies and control issues involved in a fully integrated system versus the theoretical ideals in the model. This paper presents and discusses the results of an integrated engineering development unit test.

Introduction

Currently on the International Space Station's (ISS) U.S. Segment, carbon dioxide (CO_2) is scrubbed from the cabin by a 4-Bed Molecular Sieve (4BMS) Carbon Dioxide Removal Assembly (CDRA) and vented overboard. The Environmental Control and Life Support System (ECLSS) prior to launch and activation of the Regenerative ECLSS racks is limited to this approach. However, the Regenerative ECLSS racks provide a second CDRA unit and an electrolysis-based Oxygen Generation Assembly (OGA) in addition to

a scar suitable for providing a CO_2 Reduction Assembly (CRA) as an alternative to venting the CO_2.

A flight experiment was proposed that would take the CO_2 removed from the cabin, and via the catalytic Sabatier process, reduce it with hydrogen (H_2) from the electrolysis-based OGA. The resulting water produced in a Sabatier reactor could perhaps provide cost and logistics savings for ISS by reducing the amount of water periodically re-supplied to orbit. To make this concept viable, a means of collecting and storing the CO_2 from the CDRA was defined and developed. To perform this task, a mechanical piston compressor along with an accumulator vessel was selected. The compressor, accumulator and Sabatier system will be packaged together as one unit. This unit is referred to as the CRA.

Testing was required to evaluate the 4BMS CDRA, compressor and Sabatier performance when integrated together. This performance had been numerically modeled and simulated; however, testing was necessary to verify the results from the engineering analyses. Testing also allowed a better understanding of the practical inefficiencies and control issues involved in a fully integrated system versus the theoretical ideals in the model.

Full up integrated testing was conduced at NASA's Marshall Space Flight Center (MSFC) in Feburary and March of 2005. The test objectives were to:

- Provide understanding of transients and integration issues
- Validate baseline operation/control logic for compressor
- Validate FORTRAN integrated model of 4BMS, compressor, and Sabatier
- Validate compressor model

This paper discusses the results of the integrated testing and provides a list of lessons learned as the result of integrated testing. Model validation via comparison of model preditions with test results is currently in work and will not be discussed in this paper. Model validation results are anticipated to be presented at the 2006 International Conference on Environmental Systems (ICES) conference.

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Hardware Description and Configuration

4-Bed Molecular Sieve (4BMS)

The 4BMS uses a four-bed molecular sieve process consisting of two desiccant beds and two CO_2 sorbent beds. Ancillary components include a blower, an air save pump, bed heaters, heat exchanger, valves, and sensors. The two desiccant beds and two sorbent beds are used alternately. Cabin air is drawn through one desiccant bed to remove the moisture from the process air, and then through one CO_2 sorbent bed to remove the CO_2.

The processed air is then sent through the second desiccant bed to remove the water previously adsorbed on the desiccant before returning the scrubbed air back to the cabin. Meanwhile, the second CO_2 sorbent bed is being heated to desorb the CO_2. Before exposing the heated bed to space vacuum, the ullage air is pumped out. Figure 1 shows the 4BMS schematically. The Performance and Operational Issues System Testbed (POIST) 4BMS unit located in the Laboratory Module Simulator (LMS) located at MSFC was used for this testing.

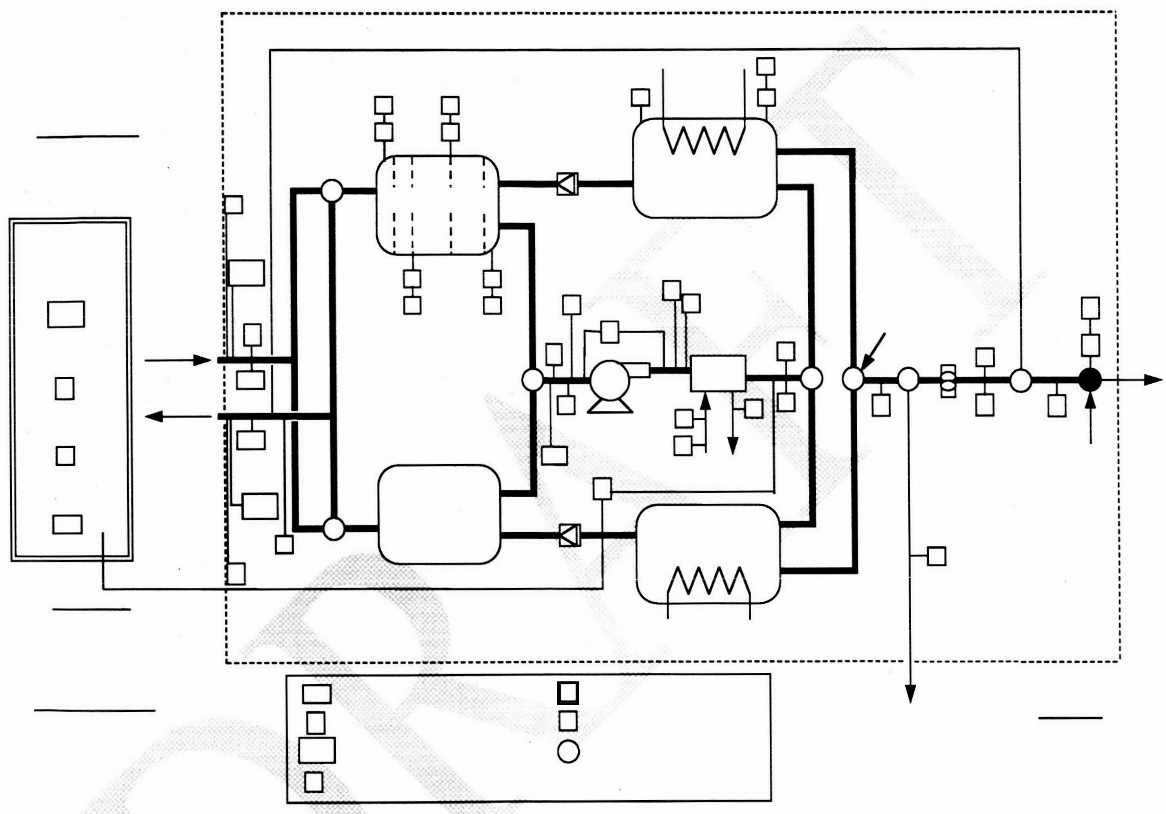

Figure 1 - POIST 4BMS Assembly Schematic

Mechanical Compressor Engineering Development Unit

As mentioned, a mechanism is needed for removing the CO_2 from the 4BMS and transferring it to the Sabatier. A mechanical two-stage, reciprocating piston design with three in-line cylinders, developed by Southwest Research Institute, was chosen and fabricated for this application. There were two first stage pistons and one second stage piston. Since the compressor gas will be processed by downstream systems, the design was an oil-less design. There was a 2 micron filter on the inlet suction line to trap any dust particles that may have evolved off the 4BMS beds. The compressor was actively cooled with 65°F chilled water representative of the medium temperature loop (MTL) on ISS. At median pressures of 4 psia suction and 70 psia discharge, the CO_2 flow was roughly 17.7 scfh (1.9 lb/hr).

To reduce compressor run time, operating rules were established and programmed into the integrated control system as listed in Table 1. P_{ACCUM} is the compressor discharge or accumulator pressure while $P_{SUCTION}$ is the compressor suction or 4BMS desorbing bed pressure.

Table 1 - Compressor Operating Rules

Compressor Transition	Transition Conditions		
	P_{ACCUM} (psia)		$P_{SUCTION}$ (psia)
Standby to Operate	>=100 AND <120	AND	> 7.5
	>25 AND <100	AND	> $P_{ACCUM}/58 + 3.6$
	<=25	AND	> 1.0
Operate to Standby	> 40	AND	< $P_{ACCUM}/58 + 1.5$
	<= 40	AND	< 0.5
	>130		NA

Accumulator

Due to the chromatographic nature of CO_2 desorption from molecular sieves, resulting in short time-span waves of CO_2 flow, and the Sabatier requirement for constant inlet CO_2 flow, a buffering capacity is needed to properly integrate a 4BMS and a Sabatier. This was accomplished with a 0.73 ft^3 accumulator. Due to space limitations within the OGA rack where the CRA hardware would be located on orbit, the total accumulator volume is constructed of several small vessels ganged together. The accumulator configuration/volume used for this test closely matches the current scar on the OGA rack.

Sabatier Engineering Development Unit (EDU)

The Sabatier EDU, developed by Hamilton Sundstrand, was designed to simulate the planned flight configuration of the CRA for ISS. As mentioned, the CRA is an integral part of a closed loop air revitalization system and makes use of both CO_2 from 4BMS and H_2 from the OGA, which would otherwise be vented. The CO_2 is combined with H_2 to produce methane (CH_4) and water (H_2O) as shown in the reaction below. The water and methane may then be used for other processes. In the case of ISS, the water would be sent to the waste water bus and processed to potable quality for use by the crew. The methane would be vented overboard as a waste product.

$$CO_2 + 4\,H_2 \longrightarrow 2\,H_2O + CH_4$$

The Sabatier EDU consisted of a Sabatier methanation reactor, a condensing heat exchanger, a gravity phase separator and the accompanying valves and sensors to provide for safe operation. The EDU is shown schematically in Figure 2.

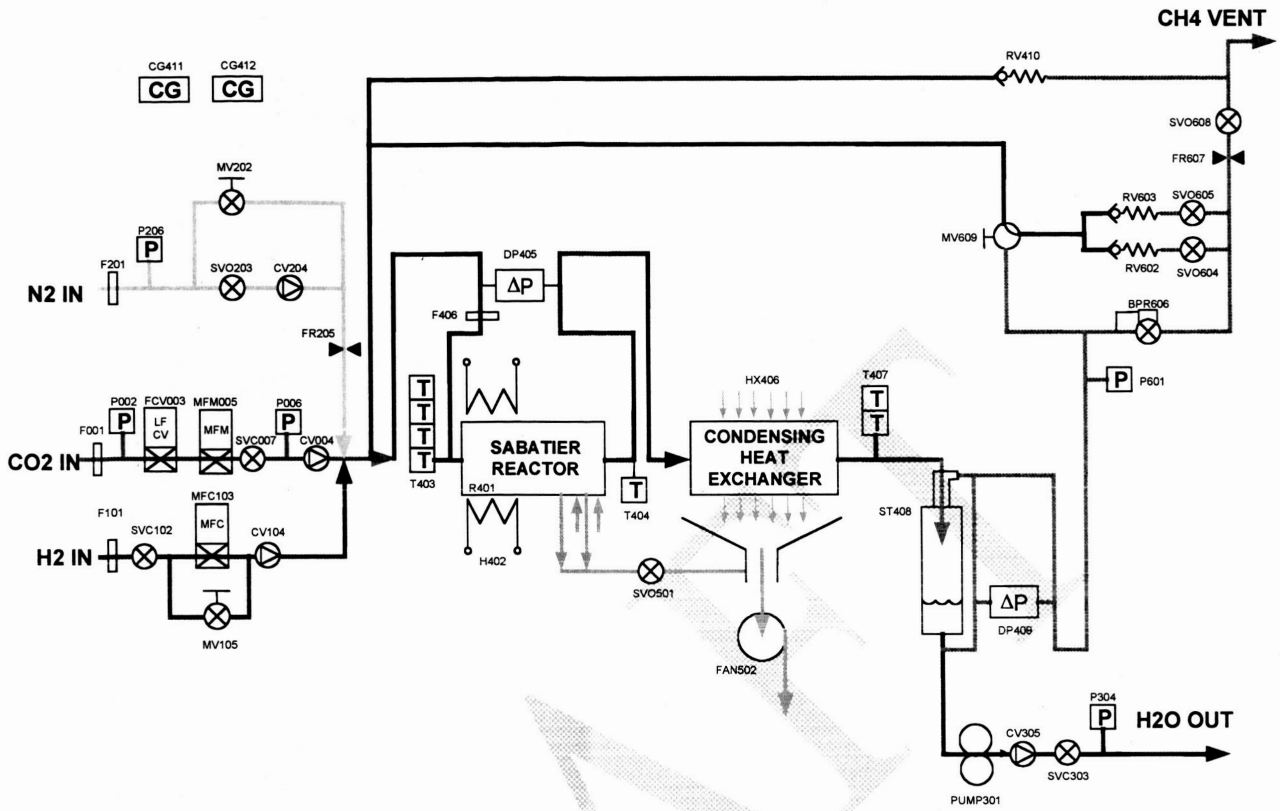

Figure 2 - Sabatier EDU Schematic

The Sabatier EDU had two primary modes of operation: Process and Standby. In Process mode, inlet gas flows through the system and methane and water were produced. To ensure that there was no possibility of combustible gasses leaking out to the atmosphere surrounding the unit, the system was operated sub-ambient. In Standby mode, supply gasses were isolated, coolant air stopped, the unit was evacuated to below 1 psia, then the system was isolated. As necessary, reactor heaters could cycle on in standby to maintain reactor temperature between 250°F and 300°F.

In Process mode, the Sabatier EDU operated at a 3.5 H_2 : 1 CO_2 molar ratio (MR). This represented about 14% excess CO_2 over the stoichiometric mixture of 4 H_2: 1 CO_2. The H_2 set point was determined based a manual per the test matrix to simulate an OGA output setting. The necessary CO_2 flowrate for a 3.5 MR was determined by the EDU controls. The inlet CO_2 and H_2 gasses were fed to a catalytic reactor. In the reactor, the gasses combined to form methane and water vapor. These products were subsequently cooled in an air-cooled condensing heat exchanger where the water was condensed to liquid. The mixture was then separated in a gravity dependent phase separator. The CH_4 and excess unreacted gasses were vented to a facility combustible gas vent through a combustible gas compatible vacuum system. Pressure differential was used to monitor the level of the liquid in the phase separator. When the delta P reached a pre-determined high point, a water transfer pump operated for a fixed period of time to reduce the water level to the lower operating level of the separator.

Integrated Test Configuration
Figure 3 below, is a schematic of the integrated system. Incorporated into the schematic was the ability for the 4BMS and compressor to operate integrated together but isolated from the Sabatier or the accumulator.

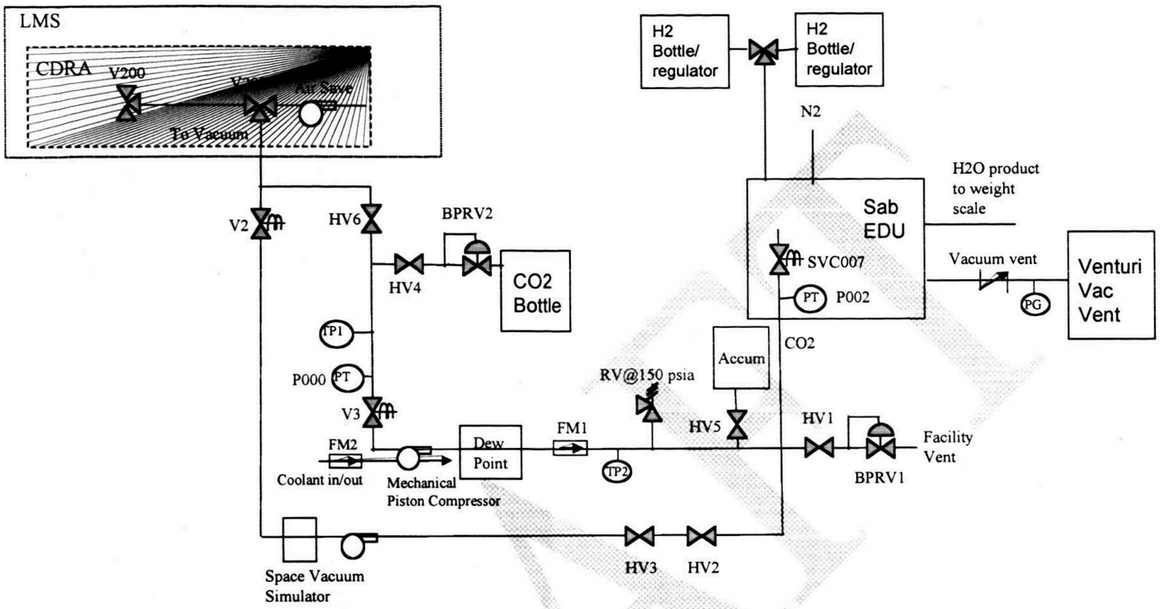

Figure 3 - Integrated Test Schematic

The POIST 4BMS was operated in nominal ISS US CDRA mode. Half-cycle time was 144 minutes, and process air flowrate was 95 lbs/hour average. For the last 10 minutes of the desorb cycle, the desorbing bed was exposed directly to the space vacuum simulator pump.

When the 4BMS and compressor are integrated together it is important that the 4BMS desorbing CO_2 sorbent bed pressure remains below a unspecified pressure that would open a spring operated check valve and release CO_2 from the bed. For conservatism, this pressure was set at 10 psia. Table 2 reflects rules for 4BMS venting to control this condition yet minimize the amount of CO_2 lost to space vacuum. During 4BMS venting, V2 (reference Figure 3) functions as the standoff CO_2 valve referenced below.

Table 2 - 4BMS CO_2 Venting Rules

Standoff CO_2 Valve Position	Portion of 4BMS Cycle (minutes)	Condition		
		Suction Pressure (psia)	Duration (seconds)	Current Compressor Operation
Closed	0 to 10	All	NA	NA
	10 to 134	< 8.0	NA	OFF
		< 10	NA	ON
Open	10 to 134	> 8.0	20	OFF

		> 10	20	ON
	134 to 144	All	NA	NA

During testing, CO_2 was injected into the 4BMS inlet as required per the test matrix (see Table 3) to simulate a range of 3 person crew without animals to 6 person crew with animals with a CO_2 loading of 0.22% and 0.46%, by volume respectively. During cyclic operation, the system mimicked current planned ISS protocol for power savings during the "night" cycle when sunlight is not available and therefore less available power. During the "night" cycle, 4BMS desorbing bed heaters are turned off and the OGA goes into standby, hence H_2 is not available. The lack of H_2 results in the Sabatier going into standby during the "night" cycle.

Table 3 - Integrated Test Matrix

test Point	CDRA CO2 Load (mmHg) (%)	EP total	Russian Vozdukh operation (on=25% CO2 load)	Russian Elecktron load (EP)	US H2 feed rate (lb/hr)*	US H2 feed rate (slpm)*	H2/CO2 molar ratio	Sabatier CO2 feed rate (lb/hr)	Sabatier CO2 feed rate (slpm)	day/night cyclic or continuous	Minimum number HC required	Compressor speed (rpm)	Modeling CDRA Location	day/night duration (min)
1	1.5 (0.2%)	3	off	0	0.029	2.461	3.5	0.183	0.703	continuous	3	1000	-	53/37
2	1.5 (0.2%)	3	off	0	0.049	4.179	3.5	0.310	1.194	day/night	4	1000	-	53/37
3	1.5 (0.2%)	3	off	0	0.049	4.179	3.5	0.310	1.194	day/night	4	800	-	53/37
4	3.5 (0.46%)	7.25	on	2	0.051	4.289	3.5	0.318	1.225	continuous	3	1000	-	53/37
5	3.5 (0.46%)	7.25	on	2	0.086	7.282	3.5	0.540	2.081	day/night	4	1000	-	53/37
6	3.5 (0.46%)	7.25	on	2	0.086	7.282	3.5	0.540	2.081	day/night	4	800	-	53/37
7	5.7 (0.74%)	7.25	off	0	0.103	8.724	3.5	0.647	2.493	day/night	4	1000	-	61/29
8	met profile	6	off	0	0.103	8.724	3.5	0.647	2.493	day/night	50 hrs	1000	Node3	53/37
9	met profle	6	off	0	0.103	8.724	3.5	0.647	2.493	day/night	48 hrs	1000	Lab	53/37
10	met profile	7.25	on	2	0.086	7.282	3.5	0.540	2.081	day/night	50 hrs	1000	Node 3	53/37
11	met profle	7.25	on	2	0.086	7.282	3.5	0.540	2.081	day/night	48 hrs	1000	Lab	53/37
12	met profile	3	off	0	0.049	4.179	3.5	0.310	1.194	day/night	50 hrs	1000	Node 3	53/37
13	met profile	3	off	0	0.049	4.179	3.5	0.310	1.194	day/night	48 hrs	1000	Lab	53/37

*includes air leakage compensation of 0.24 lb/day air

Metabolic profiles for test points 8-13 above were generated using an integrated model that was developed at NASA JSC that allowed for atmosphere mixing and air revitalization hardware analysis of multiple integrated modules as configured on ISS (1). Assumptions were made as to crewmember's movements based on where sleep stations, work stations, galley, and exercise equipment was located. The metabolic generated CO_2 rate used was as defined in NASA document SSP41000. The CO_2 profile in the module where the CDRA was located was the profile that was injected into the 4BMS during integrated testing. Note that location of the CDRA on ISS was evaluated for both the Lab module as well as Node 3.

Both influent CO_2 and product Sabatier gasses were sampled at least once per test point and measured for purity. Sabatier product water was also periodically collected for analysis.

Question - prior to test, installed filters downstream of sorbet beds in order to evaluate effectiveness with bed that has breached containment design as currently experiencing on orbit. – want to discuss at all?

Test results

In November 2004, integrated testing between the 4BMS and the compressor alone was conducted. The purpose of the testing was to verify that any moisture coming off the

4BMS would not condense and result in liquid water buildup within the compressor. The 4BMS was operated as defined above, but the discharge of the compressor was held constant at 20, 47.5, 75, 102.5 or 130 psia depending on the test point. Since the compressor operating rules defined above were in place, the compressor cycled on/off depending on the pressure ranges it experienced. This resulted in a cyclic outlet dew point profile that was more a function of the compressor turning on/off than actual outlet dew point measurements. When the compressor was operated for any length of time, there was a significant decrease in measured outlet dew point. However, since in all cases the maximum dew point was approximately 30°F or 35° below the 65°F heat rejection coolant loop, liquid condensation within the compressor was determined not to be a concern.

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In addition to this evaluation, a low moisture dew point analyzer was configured to sample the inlet as well as the outlet of the 4BMS sorbent bed during adsorb phase. This was the first time this measurement had been made. Previously, given the isotherms for the sorbent material, it was through that all moisture that entered the sorbent bed was adsorbed and removed during the desorbe phase. Test results found that under nominal operating conditions, both the inlet and outlet dew point to the sorbent bed was -80°F indicating that at low vapor pressures, moisture passes through the bed instead of being adsorbed.

Given the results of the adsorb phase inlet/outlet dew point measurements, the elevated dew points observed during the 4BMS/compressor testing could have been the result of in-leakage. Overall, more study should be put towards understanding the moisture balance around the sorbent beds. From the results of the above testing as well as low moisture measurements that were taken on 4BMS product CO_2 in the fall of 2002 (2), it does not appear as through moisture carry over and condensation in the compressor is an issue for developing a successful CRA.

Due to a series of hardware anomalies that will not be discussed in this paper, actual full-up integrated testing did not begin until February 2005. In the interest of time, after comparing the analytically generated cabin metabolic profile for test point 8 vs 9 and test point 12 vs 13, it was decided to skip test points 9 and 13. In these instances the overall metabolic profile, weather hardware was located in the Lab or Node 3 module, was very similar. The primary difference was that for test point 8 and 12, the cabin partial pressure CO_2 levels had sharper peeks and were considered to be "worst case" as compared to 9 and 13. See [redacted] below for clarification.

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

General observations that were made during test include the following:

- Occasionally the compressor would be "on" during the night cycle. If this did happen, typically it would be no more than a few minutes at the beginning for the night cycle. The compressor did not run at any other time in the night cycle other than at the very beginning.
- A decrease in accumulator pressure was observed while in standby state. It is assumed this is due to leakage, weather externally or through the Sabatier system. During standby state, Sabatier system pressure begins to decrease approximately half way through the night cycle. Again this could be due to valve leakage or simply the appearance of leakage and the system cools. In the case of valve leakage, it is not anticipated that that this will be a problem in the flight design due to pedigree of flight hardware.
- In the current configuration, CO_2 flow is allowed to vary $\pm$ 0.04 slpm of the desired set point. It was observed that regardless of accumulator pressure, when the accumulator pressure was increasing, actual CO_2 flow was above desired set point. When accumulator pressure was decreasing, CO_2 flow was below desired set point.
- Fluctuations in CO_2 flow around set point does not seem to have impact on reactor temperatures.
- Flow rates directly effect sabatier system pressures as would be expected.

During test point 12 and 7 (last two test points conducted) it was found that the mass of CO_2 injected into the 4MBS did not match the desired for one side of the 4BMS even through the concentration was as specified in the test matrix. While not thoroughly investigated yet, at the time of this reporting it is believed that there was a decrease in air flow as the result of an increased delta pressure across one of the sorbent beds. With decreased air flow, less CO2 was required to maintain the desired CO2 concentration as

programmed into the controller. The decreased air flow is most likely the result of particulate buildup on the sock filters that were installed on the sorbent beds prior to integrated testing, to replicate the current ISS configuration. Note that the CDRA sorbent bed containment design is currently being re-evaluated so this should not pose a problem in future testing or a flight design. For the purposes of collecting data to validate analytical models, these cases will be re-run at a future date with the 4BMS, accumulator, and compressor integrated together. The Sabatier will be simulated by a representative constant removal rate from the accumulator.

Lessons learned

As in any test, there were several observations made that would qualify as a "lessons learned" for future development.

During initial testing of the compressor by the vendor, it was found that there was unexpected, excess heat on the pistons. It was thought that the motor was dissipating additional heat into the crank case than was originally considered, thereby leading to higher temperatures in the crankcase and piston guide bores. A heat exchanger was designed to wrap around the crankcase to provided additional cooling. It was then discovered that the motor and controller performance was not optimized resulting in undesired current flows which could have resulted in the observed waste motor heat. Phase and current data were taken and compared to the manufacturers printed data for the same type motor. The measured data appeared to be directly opposite that of the manufacturer's data. Also the power measured going into the motor controller was high. To resolve this, the original Kollmorgen motor amplifier was replaced with an Advanced Motion Controls model that provideed more acceptable (i.e., less noise and sharper transitions) motor current waveforms. The replacement controller resulted in a quieter operation and a slight reduction in motor waste heat. The lesson learned was that sometimes a simpler controller (i.e., advanced motion controls model) is better. The Kollmorgen design had additional complexity that may have resulted in difficulty in tuning and control of the motor.

In the original configuration of the Sabaiter, there was a section of tygon tubing downstream of the phase separator and upstream of the water product line check valve. During testing, it was found that interfaces to the tubing were difficult to seal and were suspected of in-leakage, especially during standby operation. In addition, the seal on the water transfer pump was also suspect to in-leakage. To remedy this, the check valve on the water product line (see Figure 2) was relocated to directly downstream of the phase separator and upstream of the pump. This greatly improved the system's ability to achieve and maintain required vacuum during steady state. For a flight design, this will not be an issue because the pump design will be different and all lines will be hard lines.

Modifications were made to the Sabatier control system to change the allowable buffer period for system pressures to stabilize at the transition to a process state as well as the transition to standby state mode from two minutes to three minutes. In some test cases,

the system was occasionally alarming and automatically shutting down and securing itself at transition from standby to process due to high pressure spikes. Similarly, in some test cases additional time was needed to pump system pressure below 2 psia at the transition from process to standby state. If the flight control logic will include similar buffers, significant testing will be required to verify that allotted buffer times are adequate over the entire operational range and that they to not impose a safety or system health problem since shutdown alarms are in-active during the buffer phase.

In preparation for integrated testing it was found that the off the shelf H_2 and CO_2 flow meters, calibrated in standard liters per minute, referenced different conditions as "standard". This resulted in an error of 7% when determining molar ratios. Additional care to details will be taken into account in future efforts.

A significant observation learned from integrated testing was that hardware leakage can be masked if hardware is leak-checked while not in operation. For example, in the current flight protocols, CDRA leakage is certified with the system non-operational. During initial integrated testing, significant air in leakage was observed on the 4BMS. Initially the check valve upstream of the sorbent bed was suspect because historically debris has effected the ability of the valve to seal correctly. However, after significant troubleshooting it was determined that a selector valve between the 4BMS blower and the sorbent beds, valve CDP-mz13 in Figure 1, was getting cold soaked during operation that resulted in shrinkage of internal soft goods and therefore leakage. In this instance the problem was resolved by tightening the valve, but it brings up a valid concern regarding current leak certification procedures.

PLEASE expand and clarify on the above anything I may have gotten incorrect. There was also concern regarding leakage across the compressor. I remember that Lee was suspecting this. Care to add some discussion on this and how this may effect flight design? Also, are there any lessons learned regarding the leak in the reactor prior to testing that should be discussed? I'm remembering the leak was found when the reactor was leak checked as a stand alone item. I just took some disassembly of the reactor to actually find the leak.

Conclusions

[redacted]

References

1. Jeng, Frank F., et al., "Analyses of the Integration of Carbon Dioxide Removal Assembly, Compressor, Accumulator, and Sabatier Carbon Dioxide Reduction

Assembly", Paper 2004-01-2496 presented at 34th International Conference on Environmental Systems, Colorado Springs, CO, 2004.

2. Wormhoudt, Joda, et al., "Measurement of Trace Water Vapor in a Carbon Dioxide Removal Assembly Product Stream," Paper 2004-01-2444 presented at 34th International Conference on Environmental Systems, Colorado Springs, CO, 2004.

Acronym List

ISS	International Space Station
CO_2	Carbon Dioxide
4BMS	4-Bed Molecular Sieve
CDRA	Carbon Dioxide Removal Assembly
ECLSS	Environmental Control and Life Support System
OGA	Oxygen Generation Assembly
CRA	CO_2 Reduction Assembly
H_2	Hydrogen
CH_4	Methane
H_2O	Water
LMS	Lab Module Simulator
CCAA	Common Cabin Air Assembly
EDU	Engineering Development Unit
POIST	Performance and Operational Issues System Testbed
LMS	Laboratory Module Simulator
MSFC	Marshall Space Flight Center
MTL	Medium Temperature Loop
MR	Molar Ratio